

Design of a 60 GHz Band 3-D Phased Array Antenna Module Using 3-D SiP Structure

Yuya Suzuki, Satoshi Yoshida, Suguru Kameda, Noriharu Suematsu,
Tadashi Takagi and Kazuo Tsubouchi
Research Institute of Electrical Communication, Tohoku University
Katahira 2-1-1, Aoba-ku, Sendai 980-8577, Japan
Email: yysuzuki@riec.tohoku.ac.jp

Abstract—A 60 GHz band 3-D phased array antenna module using 3-D system-in-package (SiP) structure is proposed and designed. Two separated 2×2 end-fire dipole array antennas on different (z - y and z - x) planes are configured in a multi-stacked substrate module. For x -direction, z - y plane array antenna is used and for y -direction, z - x plane array antenna is used. In order to achieve higher antenna gain at intermediate region between x and y directions, hetero-plane beam synthesis using the two separated array antennas is proposed. The simulated result shows 10 dBi beam coverage area of 150° in azimuth and 60° in elevation.

I. INTRODUCTION

Wireless systems using license-free 60 GHz band have been focused for Gbps ultra-high speed data rate short range communication. The IEEE 802.15.3c STD, published in 2009, defined the specification of beamforming transceiver for 60 GHz wireless personal area network (WPAN) system. Various beamforming array antennas for 60 GHz band WPAN have been developed. Broadside patch array antennas [1], [2] have been widely used due to their easy integration on a substrate surface (uni-plane). 2-dimensional array can be realized, but the coverage is limited to within $\pm 45^\circ$ from the perpendicular axes. In order to obtain wider coverage, end-fire antenna composed of two 1×4 quasi-Yagi arrays oriented orthogonally has been proposed [3]. Since two arrays are oriented orthogonally, coverage of the azimuth is over $\pm 45^\circ$.

In this paper, we propose a 3-D phased array antenna module having two separated 2×2 end-fire dipole array antenna. These antennas are orthogonally integrated in a stacked substrate module fabricated in 3-D SiP technology [4]–[7]. A 2×2 array antenna allows the beamforming functionality in both azimuth and elevation directions [6], [7]. By combining the beams emitted from two separated array antennas (hetero-plane beam synthesis), wider coverage in azimuth direction can be obtained which exceeds twice of each array antenna.

II. CONFIGURATION OF PROPOSED 3-D PHASED ARRAY ANTENNA MODULE

The overview of the proposed 60 GHz band 3-D phased array antenna module is shown in Fig. 1. Five multilayered organic substrates are vertically stacked using 3-D SiP technology. In order to realize wide coverage in the azimuth, 2×2 dipole phased array-A and B are populated on the $+x$ and $+y$ direction, respectively. A-plane and B-plane are defined as a plane perpendicular to the $+x$ and $+y$ -axis, respectively.

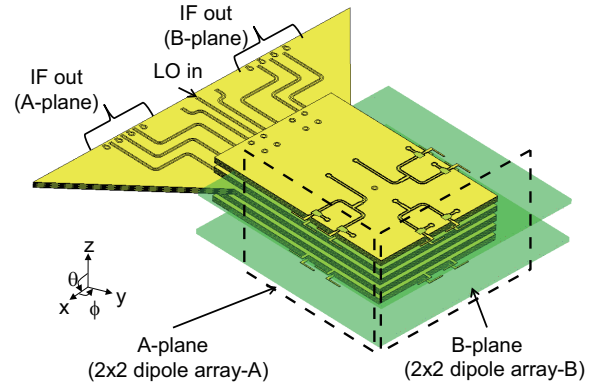


Fig. 1. Overview of the 60 GHz band 3-D phased array antenna module using 3-D SiP structure.

A block diagram of the proposed 3-D phased array antenna module is shown in Fig. 2. Eight passive 60 GHz band double balanced MMIC diode mixers (HMC-MDB169, Hittite Microwave Corporation) were used as downconverter. A conventional T-junction was used to split the LO signal. To evaluate 3-D radiation patterns, the amplitude and phase of the received signal in each direction are measured for each element antennas [8]. Since 60 GHz multichannel measurement of the amplitude and phase is quite difficult, eight passive mixers are used for downconverting the received RF signal to an IF signal at each element antenna. The amplitude and phase of the downconverted IF signals are measured by multichannel oscilloscopes. Frequency of the IF signal is 1 MHz to allow observation of both amplitude and phase using a multichannel oscilloscope. By controlling the phase of each IF signal, beamforming is realized.

The structure of the 60 GHz band 3-D phased array antenna module using 3-D SiP structure is shown in Fig. 3. A side view of the module is shown in Fig. 3(a). Five multilayered organic substrates are vertically stacked using 3-D SiP technology. MEGTRON6 substrate (Panasonic Electric Industry Co.) is used as multilayered organic substrates. Datasheet values of 3.5 for relative permittivity and 0.002 for dielectric loss tangent at 2 GHz are used in the EM simulation. Copper ball interconnections are used in the 3-D SiP structure for the 60 GHz band LO signal transmission [9] and the 1 MHz IF signal transmission. The copper balls are soldered and fixed, and serve to bond and support the various substrates. The planar dipole antennas are located on the top and bottom

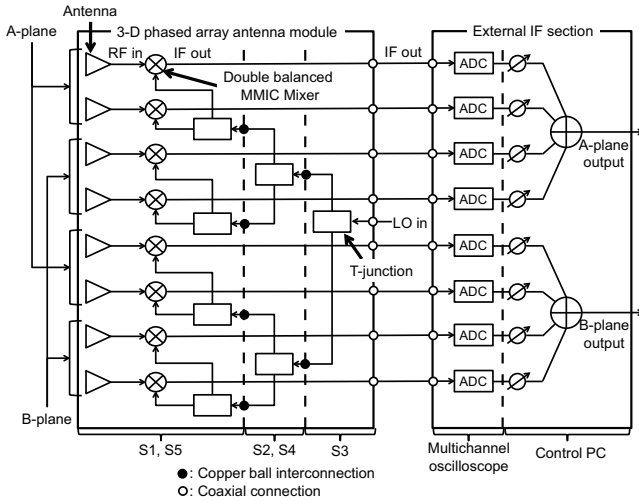


Fig. 2. Block diagram of the proposed 3-D phased array antenna module.

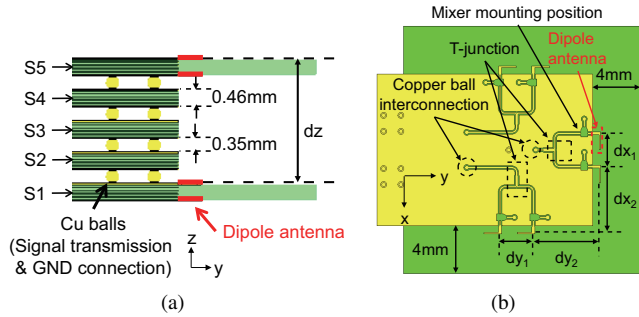


Fig. 3. Structure of the 3-D phased array antenna module using 3-D SiP structure: (a) side view and (b) front view of top substrate S5.

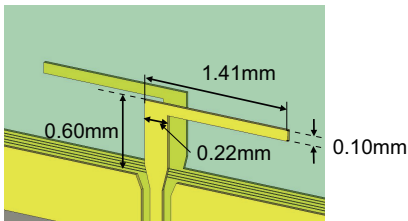


Fig. 4. Structure and dimension of the element antenna.

substrate. Vertical element spacing dz is $0.65 \lambda_0$. λ_0 is defined as free-space wavelength at 60 GHz. S2 and S4 substrates are used to provide a wide dz spacing (about one-half wavelength). A front view of top substrate S5 is shown in Fig. 3(b). The pattern of bottom substrate S1 is same as S5 substrate, but S1 substrate is inverted. Therefore, the signal line and mixer mounting position of S5 substrate are placed on its top layer, but those of S1 substrate are placed its bottom layer. The 60 GHz band LO signal is equally divided for eight passive mixers using T-junctions in the substrates. The substrate length (the length as measured from the top edge of the grounded coplanar waveguide (GCPW)) is 4 mm. This length results in a -3 dB beamwidth of 90° in both the ϕ and θ directions [7]. dx_1 and dy_1 are defined as horizontal element spacings of dipole array-B and A, respectively. And their values are both $0.50 \lambda_0$. dx_2 and dy_2 are defined as the distance in the x - and y -axis direction between dipole array-A and B, respectively.

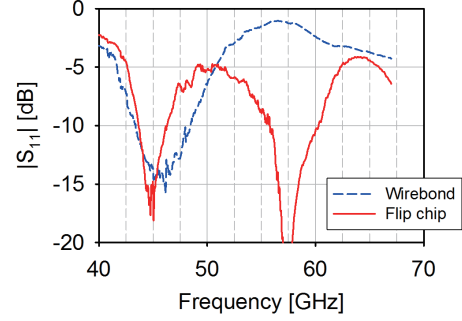


Fig. 5. Comparison of measured return loss of mounted MMIC mixer.

In the next section, these are set as a parameter to analyze the impact on the gain and beamwidth when hetero-plane beam synthesis is performed. A structure and dimension of the element antenna is shown in Fig. 4. The dipole antenna is placed on the substrate's top and bottom surfaces. The antenna is fed by a 0.60 mm pair line, which is directly connected to the GCPW. The one-sided antenna length is 1.41 mm [10].

When the proposed phased array antenna module is measured as a receiver, a part of received signal of the element antenna is reflected from the RF port of mixer. These phenomenon results in fluctuation of phase and amplitude of received signal. Therefore, it is necessary to reduce reflection at input port of mixer. The measurement results of return loss of the mixer mounted by wire bonding and flip-chip mounting is shown in Fig. 5. It is confirmed that flip-chip mounting has better return loss characteristic than wire bonding at 60 GHz band. Therefore, flip-chip mounting is selected in this work.

III. ARRAY DESIGN FOR HETERO-PLANE BEAM SYNTHESIS

Proposed 3-D phased array antenna module can realize wider coverage in the azimuth direction by switching the dipole array-A and B. However, the gain drops as the scanning angle becomes large. Therefore, it is difficult to cover the intermediate region (around $\phi = 45^\circ$) by only switching between dipole array-A and B. To solve this problem, hetero-plane beam synthesis using the two separated array antennas is proposed. The beam synthesis is realized by combining the beams emitted from two separated phased arrays (dipole array-A and B). The dipole array-A and B are oriented orthogonally but the polarization is parallel to the azimuth plane. Therefore, hetero-plane beam synthesis is available in the intermediate region.

An example of EM simulation results of hetero-plane beam synthesis is shown in Fig. 6. EM simulation software Microwave Studio (Computer Simulation Technology Co.) was used. A 3-D radiation pattern in which only dipole array-A is excited at $(py, pz) = (135^\circ, 180^\circ)$ is shown in Fig. 6(a). Similarly, only dipole array-B is excited at $(px, pz) = (135^\circ, 180^\circ)$ is shown in Fig. 6(b). px , py and pz are defined as the phase difference between the adjacent elements in the x , y and z directions, respectively. These phase differences are selected assuming use of 3-bit phase shifter. Since S1 substrate pattern is reversed S5 pattern, the element antennas

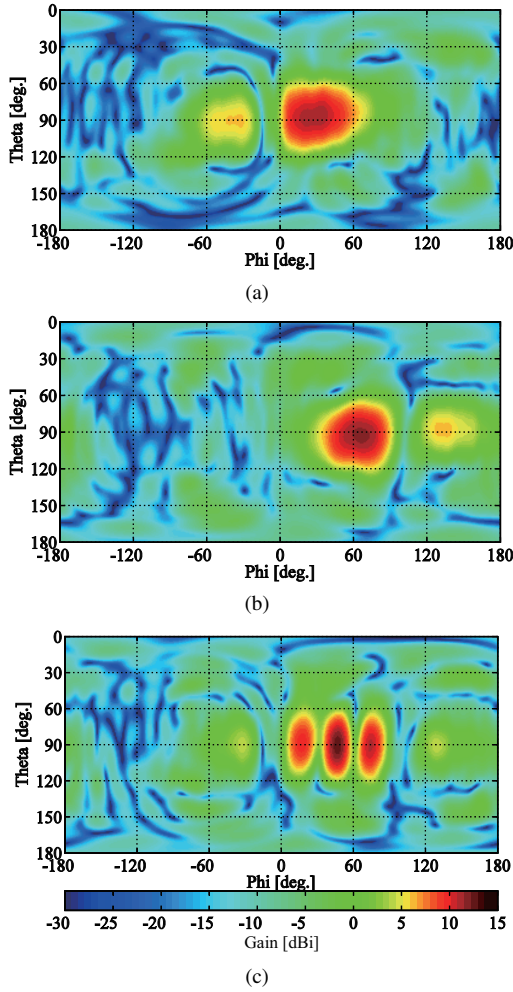


Fig. 6. Simulation results of a 3-D radiation pattern at phase difference $px = 135^\circ$, $py = 135^\circ$ and $pz = 180^\circ$ at 60 GHz ($dx_1, dy_1 = 0.5\lambda_0$, $dx_2, dy_2 = 1.0\lambda_0$): (a) only dipole array-A is excited, (b) only dipole array-B is excited and (c) hetero-plane beam synthesis pattern by simultaneous excitation both dipole array-A and B.

on S1 substrate have opposite phase to element antennas on S5 substrate. Hence, $pz = 180^\circ$ realizes the main beam direction to $\theta = 90^\circ$. Array gain in the intermediate region is less than 10 dBi when only dipole array-A or B is excited as shown in Fig. 6(a) and 6(b). Hetero-plane beam synthesis pattern by simultaneous excitation both dipole array-A and B ($dx_2, dy_2 = 1.0\lambda_0$) at $(px, py, pz) = (135^\circ, 135^\circ, 180^\circ)$ is shown in Fig. 6(c). Beam synthesis at intermediate region is confirmed and peak gain is 12.7 dBi at $(\theta, \phi) = (90^\circ, 46^\circ)$. Since the array spacing is relatively wide ($1.0\lambda_0$), sidelobe level is relatively large. However, this is acceptable because during beamforming, the optimal beam is selected. The positions of side lobes will therefore be covered by the main lobes of other beams eventually.

In order to determine optimal array spacing, parametric study using EM simulator is performed. dx_2 and dy_2 are set as a parameter to analyze the impact on the gain and beamwidth when hetero-plane beam synthesis is performed. Synthesized patterns with $dx_2, dy_2 = 0.5\lambda_0$ and $1.5\lambda_0$ are shown in Fig. 7(a) and 7(b), respectively. It is confirmed that beamwidth and sidelobe level become narrower and higher

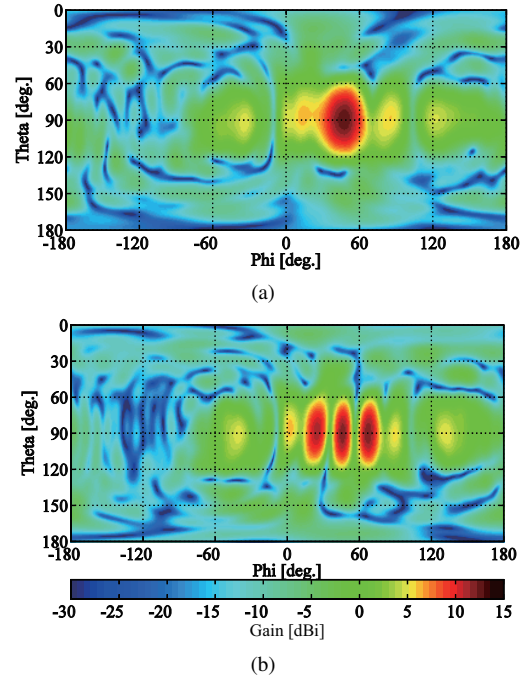


Fig. 7. Simulation results of hetero-plane beam synthesis patterns of dipole array-A and B at phase difference $px = 135^\circ$, $py = 135^\circ$ and $pz = 180^\circ$ at 60 GHz ($dx_1, dy_1 = 0.5\lambda_0$): (a) $dx_2, dy_2 = 0.5\lambda_0$ and (b) $dx_2, dy_2 = 1.5\lambda_0$.

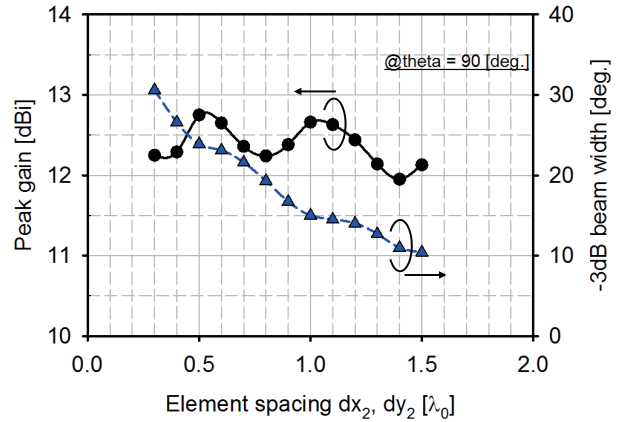


Fig. 8. Simulation results of the impact of array spacing on the gain and beamwidth when hetero-plane beam synthesis is performed ($dx_1, dy_1 = 0.5\lambda_0$).

respectively, as the spacing is extended. Simulation results of the impact of array spacing on the gain and beamwidth are summarized as shown in Fig. 8. Gain reaches a peak at $dx_2, dy_2 = 0.5\lambda_0$ and $1.0\lambda_0$. x - y plane beamwidth is more than 10° throughout simulated spacing. This value is enough for beamforming under the assumption of the use of 3-bit phase shifter. The narrow spacing results in increase of density of the feeding network. Hence, considering the actual implementation, the complexity of the implementation is reduced as the array spacing is extended. Therefore, optimal array spacing of $dx_2, dy_2 = 1.0\lambda_0$ is selected.

Simulation results of beamforming coverage area where

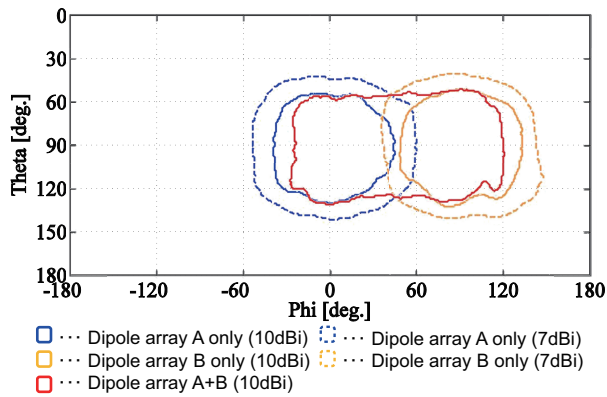


Fig. 9. Simulation results of beamforming coverage area where gain exceeds 7 dBi and 10 dBi at 60 GHz ($dx_1, dy_1 = 0.5 \lambda_0$, $dx_2, dy_2 = 1.0 \lambda_0$).

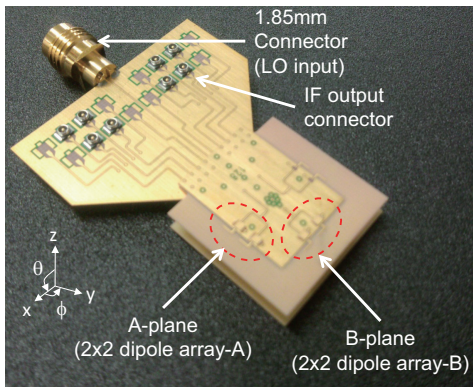


Fig. 10. Fabricated 60GHz band 3-D phased array antenna module using 3-D SiP structure.

gain exceeds 7 dBi and 10 dBi at 60 GHz are shown in Fig. 9. All the simulations are conducted under the condition of $dx_2, dy_2 = 1.0 \lambda_0$. 64 phase states are simulated to each array, assuming use of a 3-bit phase shifter. 60° beam scanning coverage area (gain of over 10 dBi) of both the azimuth and elevation are obtained at both 2×2 dipole array-A and B (blue and orange solid lines). However, the intermediate region ($\phi = 30^\circ - 60^\circ$) is not covered with 10 dBi. But 7 dBi coverage areas are overlapped (blue and orange dashed lines). Therefore, beam synthesis is available in the intermediate region. Using hetero-plane beam synthesis, the intermediate region is covered with 10 dBi gain (red solid line). These results show that the 10 dBi beam coverage area which covers 150° in azimuth and 60° in elevation is achieved by switching and hetero-plane beam synthesis of two separated array antennas.

IV. FABRICATION

A fabricated 60GHz band 3-D phased array antenna module using 3-D SiP structure is shown in Fig. 10. Five multilayered organic substrates are vertically stacked by 3-D SiP technology using $350 \mu\text{m}$ ϕ copper balls. A passive 60 GHz MMIC mixer is flip-chip mounted for each antenna element, and it downconverts RF signal into 1 MHz IF frequency. The phase of each element antenna is controlled using an external IF section. The IF output ports and LO input port are placed on the 3rd substrate. The intrinsic module size excluding I/O area is $18 \text{ mm} \times 17 \text{ mm} \times 3.7 \text{ mm}$.

V. CONCLUSION

A 60GHz band 3-D phased array antenna module using 3-D SiP structure is proposed and designed. 2×2 dipole phased arrays configured in the multi-stacked substrate module are placed orthogonally. In order to overcome a drop of antenna gain in the intermediate direction between the orthogonal array antennas, hetero-plane beam synthesis is employed. By the EM simulation, $1.0 \lambda_0$ is selected as a optimal array spacing between the orthogonal array and the edge of module. This array spacing brings higher gain and wider beamwidth for beamforming under the assumption of the use of 3-bit phase shifter with easier implementation. EM simulation results show that the proposed phased array antenna module can achieve 150° and 60° beam scanning coverage area (gain of over 10 dBi) in azimuth and elevation, respectively. Based on this study, three orthogonal end-fire phased arrays can be integrated in a module and it will show a wider beam coverage of 240° in the azimuth plane.

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